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TITLE: VARYING REFRACTIVE INDEX
OPTICAL MEDIUM USING AT
LEAST TWO MATERIALS WITH
THICKNESSES LESS THAN A
WAVELENGTH

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VARYING REFRACTIVE INDEX OPTICAL MEDIUM USING AT LEAST TWO MATERIALS WITH THICKNESSES LESS THAN A WAVELENGTH

[0001] This application claims the benefit of the filing date under 35 U.S.C. § 119(e) of Provisional U.S. Patent Application Serial No. 60/406,704, filed on August 28, 2002, which is hereby incorporated by reference in its entirety.

CROSS REFERENCES TO RELATED APPLICATIONS

[0002] This application is related to commonly assigned co pending U.S. Patent Application Serial No. 10/083,674, "Integrated Planar Composite Coupling Structures for Bi directional Light Beam Transformation Between a Small Mode Size Waveguide and a Large Mode Size Waveguide," filed October 22, 2001, the disclosure of which is incorporated herein by reference.

[0003] This application is also related to commonly assigned co pending U.S. Patent Application Serial No. ____/____ (Attorney Docket No. 10095/19), "Optical Beam Transformer Module for Light Coupling between a Fiber Array and a Photonic Chip and the Method of Making the Same," filed on the same date as the present application, the disclosure of which is incorporated herein by reference.

[0004] This application is also related to commonly assigned U.S. Patent Application Serial No. 09/884,691, "Method for Forming a Refractive Index Patterned Film for Use in Optical Device Manufacturing," filed June 19, 2001, the disclosure of which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

[0005] The present invention relates generally to structures having a refractive index distribution and in particular to an optical medium having an arbitrary desired effective refractive index distribution using at least two materials with thicknesses less than a wavelength.

[0006] Optical communication systems require optical components to guide and/or manipulate a light beam in continuous or pulse format. Of the various optical components used in optical communication systems, some have a continuous change in the distribution of the refractive index. Examples include graded refractive index multimode optical fibers [e.g., Cohen et al., "Multimode Optical Fiber," U.S. Patent No. 3,989,350, Nov. 2, 1976; Fleming, Jr., "Multimode Optical Fiber," U.S. Patent No. 4,033,667, July 5, 1977 and graded refractive index rod lenses [e.g., Ho Shang Lee, "Miniaturization of Gradient Index Lens Used in Optical Components," US Patent No. 6,088,166, July 11, 2000]. A continuous refractive index change can serve various purposes, including light beam collimation, focusing, imaging and the like [Duncan T. Moore, "Gradient Index Optics: A Review," Applied Optics, Vol. 19, No.7, 1 April 1980].

[0007] Traditionally, such graded refractive index ("GRIN") devices have been created by mixing different materials. Most of these methods involve a dominant material and another material that is either used as a dopant or dispersed in the dominant material [e.g., Park et al., "Production Method for Objects with Radially-Varying Properties," U.S. Patent No. 6,267,915 B1, July 31, 2001]. As there is generally a limit to the amount of dopant that can be uniformly distributed inside the dominant material, the maximum refractive index change (Δn) that can be achieved using such a method is generally less than 0.1. As a result, when such a method is used to make a graded refractive index lens to focus a light beam, the light focusing power of the lens is generally low. In other words, the focal length of such a lens is relatively long, and the focused beam spot size is relatively large (typically a few microns). A typical example is an ion exchanged glass based GRIN rod lens, such as lenses made by GRINTECH GmbH, for which the focal length (also called a quarter pitch) is on the order of millimeters and the focused beam spot size is on the order of a few microns.

[0008] Various techniques for producing GRIN devices having an essentially continuous refractive index change have been developed. A first method uses neutron irradiation, in which a boron rich glass is bombarded with neutrons to create a change in the concentration of boron and hence a change in the refractive

index of the material [P. Sinai, Applied Optics, Vol. 10, pp 99 (1971)]. This method has limited application because the gradient is not permanent, and the maximum index change is only about 0.02.

[0009] A second method uses chemical vapor deposition (CVD) to create a fiber preform for a GRIN optical fiber. A glass material of a given refractive index is deposited on either the inside or outside of a tube. A succession of layers having slightly different chemical compositions (e.g., slightly increased or decreased dopant concentrations) is then deposited. Each layer generates a small step in the refractive index. After the preform, which typically has a diameter of about 2.5 cm, is made, a fiber is drawn from it. As the fiber is drawn, the layers become so thin that the refractive index distribution becomes effectively continuous [e.g., Cohen et al., "Multimode Optical Fiber," U.S. Patent No. 3,989,350, Nov. 2, 1976; Fleeting, Jr., "Multimode Optical Fiber," U.S. Patent No. 4,033,667, July 5, 1977; Dabby et al., "Graded Start Rods for the Production of Optical Waveguides," U.S. Patent No. 4,298,366, Nov. 3, 1981; Dabby et al., "Graded Optical Waveguides," U.S. Patent No. 4,423,925, Jan. 3, 1984]. The maximum index change that can be achieved using this technique is about 0.01.

[0010] A third method involves producing a graded refractive index in organic or plastic materials. For instance, multiple plastic layers of successively increasing or decreasing refractive index can be deposited on a plastic cylinder or planar surface; the material is then cured [e.g., Toyoda et al., "Distributed Graded Index Type Optical Transmission Plastic Article and Method of Manufacturing Same," U.S. Patent No. 5,390,274, Feb. 14, 1995; Nakamura, "Method and Apparatus for Manufacturing Distributed Refractive Index Plastic Optical Fiber," U.S. Patent No. 6,132,650, Oct. 17, 2000]. In related processes, monomers can be changed to polymers or cross linking of polymers can be enabled using either thermal radical polymerization (induced by UV or laser light, photodimerization, or electron ray) or condensation polymerization (induced by radical addition or photodimerization) [e.g., Jung et al., "Manufacturing Method of a Polymer GRIN Lens Using Sulfonation," U.S. Patent No. 5,567,363, Oct. 22, 1996]. The disadvantages associated with plastics include the relatively strong absorption of

light in the standard communication wavelength band, as well as the relatively low thermal and lifetime stability of the plastic material. Although attempts to address these problems — e.g., by replacing the C-H bond by a C-F bond [Sugiyama et al., “Graded Refractive Index Optical Plastic Material and Method for its Production,” U.S. Patent No. 6,166,125, Dec. 26, 2000] — have been somewhat successful, the optical communication industry still generally prefers not to use plastic gradient lenses.

[0011] A fourth method, ion exchange, is commonly used to make glass-based graded refractive index rod lenses. Ions from a molten salt, e.g., lithium bromide or potassium nitrate, diffuse into glass and are exchanged with larger ions in the glass [e.g., Senapati et al., “Graded Index Lens for Fiber Optic Applications and Technique of Fabrication,” U.S. Patent No. 6,128,926, Oct. 10, 2000; Senapati et al., “Graded Index Lens for Fiber Optic Applications and Technique of Fabrication,” U.S. Patent No. 6,172,817 B1, Jan. 9, 2001]. The possible refractive index distribution is limited by the diffusion process, and the maximum refractive index change is only about 0.05.

[0012] A fifth method is ion or molecular stuffing, in which heat is applied to separate the phases of a special glass in which one of the phases is dissolvable in an acid. After acid treatment, the glass is immersed in a bath to allow other ions or molecules to diffuse into the glass pores; alternatively, the pores may be left behind. The glass is then condensed by heating [e.g., R.K. Mohr et al., Digest of Topical Meeting on Gradient-Index Optical Imaging Systems (Optical Society of America, Washington, D.C., 1979), paper WA I; Macedo et al., “Method of Producing Optical Wave Guide Fibers,” U.S. Patent No. 3,938,974, Feb. 17, 1976. However, most glasses that are well accepted for optical communication do not possess the required uniform phase separation property. In addition, the maximum refractive index change is still only about 0.05.

[0013] A sixth method involves a “sol-gel” technique, in which a solution of multiple metal oxides is spin coated or dip coated on a surface. Heat treatment follows to evaporate the solvent and condense the metal oxides, thereby forming a thin layer of glass film. To create a graded refractive index multiple layers having

different metal oxide content can be successively deposited. One problem with this technique is that cracking of the film tends to occur as the film grows thicker and the amount of dopant in the solution increases. It is thus difficult to produce a film thickness of the order of about 10 μm . In an alternative process, a gel glass film or gel glass rod can be made first, and glass phase separation can be induced by heat treatment followed by selective leaching or etching to create a microporous structure with a graded refractive index [e.g., McCollister et al., "Process of Making Glass Articles Having Antireflective Coatings and Product," U.S. Patent No. 4,273,826, Jun. 16, 1981; S.P. Mukherjee et al., "Gradient index AR Film Deposited by the Sol Gel Process," *Applied Optics*, Vol. 21, No. 2, p. 283, Jan. 15, 1982; S. Konishi et al., "r-GRIN Glass Rods Prepared By a Sol Gel Method," *Journal of Non Crystalline Solids*, Vol. 100, pp. 511 513 (1988); Debsikdar, "Broadband Antireflective Coating Composition and Method," U.S. Patent No. 4,839,879, May 16, 1989]. Again these methods can only produce a maximum index change of about 0.1.

[0014] A seventh method involves UV imprinting of photosensitive glasses to disrupt the metal oxygen bond, thereby inducing a refractive index change. This technique is commonly used to make fiber Bragg gratings (FBG), which are common components in today's fiber-optic communication systems. The most commonly used material is germanium doped silica fiber. After hydrogen loading and UV laser imprinting, the maximum index change is about 0.1. Another glass of higher photosensitivity is lead oxide, but it has been found that the maximum achievable index change for UV imprinting of lead oxide is only about 0.2 [see the above-referenced co-pending U.S. Patent Application Serial No. 09/884, 691.

[0015] An eighth method makes use of centrifugal force applied during the combustion synthesis of composite materials, with the result that the composition and particle size of the metallic or ceramic component changes continuously across the thickness of the product [e.g., Munir et al., "Centrifugal Synthesis and Processing of Functionally Graded Materials," U.S. Patent No. 6,136,452, Oct. 24, 2003. This method involves applying a glass melting high temperature to a rotating mold containing glass powder, mixtures. As in the glass melting methods

involving dopants, there is a maximum concentration of the metallic or ceramic component that can be achieved without clustering. Consequently, the maximum index change that can be achieved is small (about 0.1).

[0016] None of these methods is able to produce a maximum index change greater than about 0.2. In addition, none of these methods is able to produce an arbitrary refractive index profile with high precision because these methods generally rely in some way on diffusion of one material into another, which cannot be precisely controlled. In some applications, for instance, light coupling between a single mode optical fiber and a III-V compound semiconductor waveguide, a graded refractive index device with a maximum refractive index change greater than about 0.2 would be desirable. Such a device would provide higher focusing power and a smaller focused spot size than GRIN devices produced by existing techniques.

BRIEF SUMMARY OF THE INVENTION

[0017] Embodiments of the present invention provide a device having a graded (or distributed or gradient) effective refractive index profile with a very high maximum refractive index change. According to one aspect of the present invention a light transmitting device with a graded index of refraction includes alternating layers of two (or more) materials having significantly different refractive indices (e.g., a difference of at least 0.2). The thickness of the layers of at least one of the materials is substantially less than the effective light wavelength of interest. The effective index of refraction in a local region within the device depends on the ratio of the average volumes of the two materials in the local region; because the relative thicknesses of the layers can be made different for different layers, a graded index of refraction can be provided. Control of the layer thicknesses also allows an arbitrary refractive index profile to be provided.

[0018] According to another aspect of the present invention, a light transmitting device having a graded index of refraction includes a body made substantially of a first material, such as an amorphous material. Embedded in the body are a number of discrete structures comprising a second material (e.g.,

another amorphous material), each of the discrete structures having a size in at least one dimension substantially smaller than an effective wavelength of light in the second material. The first material has a first index of refraction and the second material has a second index of refraction different from the first index of refraction; in one embodiment, the first and second indices differ by at least 0.5. The size of the discrete structures in the at least one dimension is different in a first local region of the body than in a second local region of the body, thereby providing a graded index of refraction. In one embodiment, the discrete structures include substantially planar (or curved) layers having a size in one dimension that is substantially smaller than an effective wavelength of light in the second material. In another embodiment, the discrete structures include filamentary structures having a size in two dimensions that is substantially smaller than an effective wavelength of light in the second material. In yet another embodiment, the discrete structures include grains having a size in three dimensions that is substantially smaller than an effective wavelength of light in the second material.

[0019] According to another aspect of the present invention, a light transmitting device having a graded index of refraction includes a plurality of alternating layers of a first material and a second material, each layer of the second material having a thickness substantially less than an effective wavelength of light in the second material. The first material has a first index of refraction, and the second material has a second index of refraction different from the first index of refraction; in one embodiment, the first and second indices differ by at least 0.5. The plurality of alternating layers forms a light-transmitting medium with an effective index of refraction in a local region that depends on a local ratio of a volume of the layers of the first material to a volume of the layers of the second material. A graded effective index of refraction along a direction transverse to the layers is formed by varying the thicknesses of the layers. The thickness of each layer of the first material can also be made to be substantially less than the effective wavelength of light in the second material. Amorphous materials, such as silicon dioxide and titanium dioxide, can be used as the first and second materials. Polycrystalline materials can also be used. The layers may be planar or

curved to provide light beam focusing in two dimensions. A variety of refractive index distributions, including parabolic distributions, can be provided. The distribution can also be optimized to provide mode matching between other light-transmitting devices (e.g., between a single mode optical fiber and a III-V semiconductor waveguide).

[0020] According to another aspect of the present invention, a light transmitting device having a graded index of refraction includes a plurality of alternating layers of a first amorphous material having a thickness and a second amorphous material, each layer of the second material having a thickness substantially less than an effective wavelength of light in the second material. The first material has a first index of refraction, and the second material has a second index of refraction different from the first index of refraction. The plurality of alternating layers forms a light-transmitting medium with an effective index of refraction in a local region that depends on a local ratio of a volume of the layers of the first material to a volume of the layers of the second material. A graded effective index of refraction along a direction transverse to the layers is formed by varying the thicknesses of the layers. The refractive index profile can be controlled so as to provide a desired focused optical spot size and mode (wavefront) profile for transmitted light.

[0021] According to another aspect of the present invention, an optical module includes a substrate assembly that has a photonic chip mounting region and a groove extending toward the photonic chip mounting region. The optical module also includes an optical coupler having a graded index of refraction disposed between the groove and the photonic chip mounting region. The optical coupler includes a plurality of alternating layers of a first amorphous material and a second amorphous material, each layer of the second material having a thickness substantially less than an effective wavelength of light in the second material. The first material has a first index of refraction, and the second material has a second index of refraction different from the first index of refraction. The plurality of alternating layers forms a light transmitting medium with an effective index of refraction in a local region that depends on a local ratio of a volume of the layers

of the first amorphous material to a volume of the layers of the second amorphous material. A graded effective index of refraction along a direction transverse to the layers is formed by varying the thicknesses of the layers. A photonic chip can be mounted in the photonic chip mounting region, and an optical fiber can be mounted in the groove.

[0022] The following detailed description together with the accompanying drawings will provide a better understanding of the nature and advantages of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0023] Fig. 1 is a schematic diagram of light propagation in a medium with a parabolic refractive index distribution;

[0024] Figs. 2A-B are schematic diagrams representing the use of two materials to realize a parabolic effective refractive index distribution according to the present invention;

[0025] Figs. 2C-D are graphs of the effective index distribution as a function of position for the structure in Figs. 2A-B;

[0026] Fig. 3 is a graph of transmittance as a function of the normalized thickness of a thin layer of one optical medium sandwiched in another optical medium;

[0027] Figs. 4A-B are graphs of a computer simulation of light propagation through a parabolic refractive index distribution realized with multiple materials and with two materials, respectively;

[0028] Figs. 5A-B are graphs of simulated light coupling from a GRIN lens into a mode matched waveguide for a parabolic refractive index distribution realized with two materials and with multiple materials, respectively;

[0029] Fig. 6 is a scanning electron microscope (SEM) image of a GRIN structure realized by depositing alternating thin layers of two materials of different layer thickness on a flat silicon substrate;

[0030] Figs. 7A-B are graphs showing the measured focused spot profile and input spot profile for a one dimensional GRIN lens realized using SiO₂ and TiO₂; and

[0031] Figs. 8A-D are schematic diagrams illustrating process steps for fabricating a GRIN device from curved layers of two materials.

DETAILED DESCRIPTION OF THE INVENTION

[0032] As is generally known, light is an electromagnetic wave oscillating at high frequency. All portions of the electromagnetic spectrum are meant to be included, including but not limited to, radiowaves, microwaves, millimeter waves, infrared radiation, visible light, and ultraviolet radiation. When light travels through a dielectric medium (e.g., glass), its speed (v) is reduced relative to the speed of light in vacuum (c). The refractive index (n) of the medium is defined as $n=c/v$. The frequency of the light is unchanged, and the wavelength is reduced from λ_0 in vacuum to $\lambda_{\text{eff}} = \lambda_0/n$ in the medium.

[0033] As shown in Fig. 1, in a graded refractive index (“GRIN”) optical medium 100, the material has a refractive index $n(r)$ that decreases substantially continuously from a value of n_0 at the central axis ($r=0$) to a value of n_b at the outside border ($r=a$). In this example, $n(r)$ has a parabolic refractive index

distribution given by the formula: $n(r) = n_0 \left[1 - \Delta \left(\frac{r}{a} \right)^2 \right]$, where $\Delta = \frac{n_0 - n_b}{n_0}$.

This index distribution will cause light rays 110 propagating longitudinally through medium 100 to bend towards the central axis and to be periodically refocused. If the optical medium is cut to the right length (f), the medium can function as a lens to focus or expand and collimate a beam of light. The focal length (or quarter pitch) of such a GRIN lens is given approximately by

$$f = \frac{a\pi}{2\sqrt{2\Delta}}.$$

[0034] In general, the focused spot size for any light beam or pulse is finite. The shorter the focal length of the lens, the smaller the focused spot size. Accordingly, a smaller focused spot size can be achieved by increasing Δ (which

is dominated by the index change between the central axis and the outside border), by decreasing α (the distance between the central axis and the outside border), or both. At the same time, there is a physical diffraction limit; consequently, the smallest focused spot size of any wave will only be about the size of the wavelength in the medium where focusing occurs. In the case of a GRIN lens, the focused light beam is located near the central axis, where the refractive index is the highest. Hence, if a high refractive index material is used at the central axis, a much smaller diffraction limited beam spot size can be achieved because the wavelength of light in a material is equal to the vacuum wavelength divided by the refractive index of the material. If the focused light beam is coupled into another mode matched waveguide, a highly efficient light coupling between the GRIN lens and the waveguide can be achieved, as will be described further below.

[0035] In principle, a graded refractive index distribution can be constructed from multiple thin layers of optical media with different refractive indices. If the layer thickness is small enough, there is a negligible difference in the focusing effect between a continuously graded refractive index distribution and a step graded refractive index distribution provided by multiple thin layers of materials with different refractive indices. Accordingly, a parabolic refractive index distribution can be produced by depositing multiple thin layers of different materials selected so that the refractive index decreases with distance from the central axis.

[0036] Embodiments of the present invention employ two (or more) materials having a relatively large refractive index difference to create a structure having a graded refractive index (e.g., a parabolic distribution). By using a high refractive index material such as silicon ($n=3.4$), the refractive index at the central axis of the parabolic GRIN structure can be made quite high, and hence the spot size of the focused light beam can be quite small (e.g., less than $0.5\ \mu\text{m}$ for light having a wavelength of $1.5\ \mu\text{m}$ in air).

[0037] When an optical medium with a dimension that is substantially smaller than the effective wavelength of light is embedded in another optical medium of a different refractive index, the result is an effective refractive index with a value

between those of the two optical media. Fig. 2 illustrates the principle. A medium 200 provides an approximately continuous parabolic refractive index distribution by using multiple layers 205 of materials having different refractive index as shown in Fig. 2A. Each layer 205 is constructed from a number of thin layers 212, 214 of two materials of different refractive indices, as shown in Fig. 2B. Each material's optical thickness is substantially less than the effective wavelength of light in the material. The effective refractive index 215, illustrated in Figs. 2C-D, is approximately $n_{eff} = \frac{n_1 L_1 + n_2 L_2}{L_1 + L_2}$, where n_1 and n_2 are the refractive indexes of the two materials respectively, and L_1 and L_2 , are the total thickness of the respective materials within a local region larger than the effective wavelength of the light. This can be generalized to a medium with a mixture of two particles with different refractive indices, in which

$$n_{eff} = \frac{n_2 \left[\frac{V_1}{V_2} \frac{n_1}{n_2} + 1 \right]}{\left[\frac{V_1}{V_2} + 1 \right]},$$

in which V_1 and V_2 are the volumes of the first and second materials. Other layers in medium 200 are made of the same materials, but with different thicknesses L_1 and L_2 , thereby providing different n_{eff} .

[0038] There are concerns about the effectiveness of using two materials to achieve the effect of a real continuous refractive index distribution. One concern is the light transmission efficiency through the many optical interfaces of the structure. A second concern is how effectively this structure focuses light. A third concern is the total amount of light that will be lost when light is focused using this structure. These concerns will now be addressed.

[0039] High light transmission efficiency can be provided by using sufficiently thin layers of the two materials. As is generally known in the art and illustrated in Fig. 3, when a light beam shines through a thin film 310 of thickness d , having a refractive index n_2 , sandwiched in another optical medium 312, the light transmittance (defined as the amount of light energy transmitted through the film

divided by the amount of light energy incident onto the film) is

$$\text{given by } T(d) = \frac{I_{trans}}{I_{inc}} = \frac{(1-R)^2}{(1-R)^2 + 4R \sin^2(k_{\perp} d)}, \text{ where } k_{\perp} = \frac{2\pi}{\lambda_{eff}} = \frac{2\pi n_2}{\lambda} \cos \theta,$$

with λ being the wavelength of light in vacuum, θ being the angle of refraction in the thin film 310, and R being the reflectance of the thin film. Fig. 3 shows the transmittance of light as a function of d/λ_{eff} for a light beam traveling from silica (SiO_2 , $n_1 = 1.45$) through a very thin film (thickness d) of titania (TiO_2 , $n_2 = 2.35$) into silica again. It can be seen that when d/λ_{eff} is less than 0.1, more than 90% of the light will be transmitted. Hence, a general guideline is that when the thickness of the thin film is less than about $\frac{\lambda}{10n_2 \cos \theta}$, more than 90% of the light will pass

through the film. If the light beam shines onto the film at normal incidence (i.e. $\theta = \theta_0$), the single layer film thickness is advantageously chosen to be less than $\frac{\lambda}{10n_2}$, which is about 66nm for TiO_2 and about 100nm for SiO_2 . In GRIN-lens

focusing applications, the light wave travels paraxially along the central axis, so that the angle θ varies from 90° to about 60° . Accordingly, the fraction of light transmitted is generally more than 95% if single layer thicknesses less than $\frac{\lambda}{10n_2}$

are used.

[0040] To evaluate the focusing power of the GRIN device, light wave propagation was simulated for a first GRIN lens having a parabolic refractive index distribution made up of thin layers of numerous different materials, substantially approximating a continuous index distribution, and for a second GRIN lens made up of layers of only two materials. Figs. 4A-B show the simulation result for a parabolic refractive index distribution of

$$n(r) = n_0 \left[1 - \Delta \left(\frac{r}{a} \right)^2 \right], \text{ with } a = 5 \mu\text{m}, n_0 = 1.75 \text{ and } n_b = 1.45. \text{ Fig. 4A shows}$$

results for the a substantially continuous GRIN lens, and Fig. 4B shows results for

the two material GRIN lens. As can be seen, both GRIN lenses have similar focal lengths and focused spot sizes.

[0041] To evaluate the energy loss for light propagating longitudinally through the device, the optical energy flow was calculated based on integration over space of the standard electromagnetic energy flow vector $\vec{S} = \vec{E} \times \vec{H}$, where $\vec{E} \times \vec{H}$ are the electric and magnetic fields. Figs. 5A-B show simulation results for a two material GRIN lens and a many material GRIN lens, respectively. In both simulations, it has been assumed that there is no material absorption of light and all the interfaces are perfect. Each GRIN lens extends from point A to point D, so that the focal point is just outside the GRIN lens. A semiconductor waveguide made of Indium phosphide (InP), with its mode matched to the focused beam profile, extends from point B to point C, leaving an air gap of 1 μm between the GRIN lens and the semiconductor waveguide. Antireflection coatings have been included on both the GRIN lens end face and on the InP waveguide end face. Table 1 shows light energy transmission efficiency for each GRIN lens. The two material case is not significantly different from the substantially continuous case.

Table 1

	Two-material case	Substantially Continuous case
Fraction of light energy passed through the GRIN lens from A to B	99.9%	98.8%
Fraction of light energy passed from B to C (including mode matching)	99.7%	99.5%
Fraction of light energy within the InP waveguide at C (i.e., within 3x width of the waveguide)	95.6%	98.2%
Overall coupling efficiency	95.3%	97.7%

[0042] The foregoing analyses indicate that a GRIN device made up of alternating layers of two different materials can provide high transmission

efficiency, a short focal length, a small focused spot size, and acceptably low energy loss when coupling to a small mode size waveguide or other optical components.

[0043] Fabrication of such a structure is straightforward; existing technologies for fabricating thin film dense wavelength division multiplexing (DWDM) filters for optical communications by depositing successive layers of materials can be adapted to fabricating GRIN devices. Deposition methods that may be employed to create the structure include sputtering, chemical vapor deposition, electron beam and thermal evaporation, ion beam deposition or dual ion beam deposition (also called ion assisted deposition, or IAD), sol gel spin or dip coating and others.

[0044] One embodiment of the present invention consists of a large number (e.g., 306) of alternating thin layers of silica (SiO_2) and titania (TiO_2) on a flat silicon substrate. The thickness of each layer (in nm) for this embodiment is listed in Table 2. A thicker buffer layer of SiO_2 (1 μm) is deposited first in order to separate the GRIN device from the substrate material so that light will not leak into the substrate. Aside from the buffer layer, the thicknesses of the silica layers range from 20 nm to 70 nm, and the thicknesses of the titania layers range from 20 nm to 80 nm. In regions where the effective index of refraction is high, titanic layers are near their thickest while silica layers are near their thinnest; in regions where the effective index is low, the reverse applies.

[0045] Fig. 6 shows an scanning electron microscope (SEM) image of such a structure deposited on a flat Si substrate, and Fig. 7A shows the measurement result of such a structure acting as a one dimensional GRIN lens to focus a light beam from a standard single mode fiber into an elliptical beam; as a comparison the output beam profile from a standard single mode fiber is shown in Fig. 7B.

[0046] It should be noted that a planar layered structure would focus light only in the direction transverse to the plane of the layers (the vertical direction for horizontal layers on a substrate). In the lateral or horizontal direction, light beam size transformation can be achieved using tapered waveguide structures, e.g., as described in the above referenced copending U.S. Patent Application Ser. No. 10/083,674.

Table 2

Mtl	nm	TiO2	50	SiO2	20	TiO2	30	SiO2	20	TiO2	30	SiO2	40
TiO2	60	SiO2	20	TiO2	40	SiO2	20	TiO2	20	SiO2	40	TiO2	20
SiO2	20	TiO2	50	SiO2	20	TiO2	30	SiO2	20	TiO2	30	SiO2	50
TiO2	50	SiO2	20	TiO2	40	SiO2	20	TiO2	20	SiO2	40	TiO2	20
SiO2	20	TiO2	50	SiO2	20	TiO2	30	SiO2	20	TiO2	30	SiO2	50
TiO2	60	SiO2	20	TiO2	40	SiO2	20	TiO2	20	SiO2	40	TiO2	20
SiO2	20	TiO2	50	SiO2	20	TiO2	30	SiO2	20	TiO2	30	SiO2	50
TiO2	50	SiO2	20	TiO2	40	SiO2	20	TiO2	20	SiO2	40	TiO2	20
SiO2	20	TiO2	70	SiO2	20	TiO2	30	SiO2	20	TiO2	30	SiO2	50
TiO2	60	SiO2	30	TiO2	40	SiO2	20	TiO2	20	SiO2	40	TiO2	20
SiO2	20	TiO2	50	SiO2	20	TiO2	30	SiO2	20	TiO2	30	SiO2	50
TiO2	50	SiO2	20	TiO2	50	SiO2	20	TiO2	20	SiO2	30	TiO2	20
SiO2	20	TiO2	70	SiO2	30	TiO2	40	SiO2	20	TiO2	20	SiO2	60
TiO2	60	SiO2	30	TiO2	40	SiO2	30	TiO2	20	SiO2	30	TiO2	20
SiO2	20	TiO2	70	SiO2	20	TiO2	40	SiO2	20	TiO2	20	SiO2	60
TiO2	50	SiO2	30	TiO2	50	SiO2	30	TiO2	20	SiO2	30	TiO2	20
SiO2	20	TiO2	70	SiO2	30	TiO2	40	SiO2	20	TiO2	20	SiO2	60
TiO2	80	SiO2	30	TiO2	40	SiO2	30	TiO2	20	SiO2	30	TiO2	20
SiO2	30	TiO2	50	SiO2	20	TiO2	40	SiO2	20	TiO2	20	SiO2	70
TiO2	80	SiO2	20	TiO2	50	SiO2	30	TiO2	20	SiO2	30	TiO2	20
SiO2	30	TiO2	40	SiO2	30	TiO2	40	SiO2	20	TiO2	20	SiO2	70
TiO2	80	SiO2	20	TiO2	40	SiO2	30	TiO2	20	SiO2	30	TiO2	20
SiO2	30	TiO2	50	SiO2	20	TiO2	40	SiO2	20	TiO2	20	SiO2	70
TiO2	80	SiO2	20	TiO2	30	SiO2	30	TiO2	20	SiO2	30	TiO2	20
SiO2	30	TiO2	40	SiO2	20	TiO2	40	SiO2	20	TiO2	30	SiO2	20
TiO2	80	SiO2	20	TiO2	40	SiO2	30	TiO2	20	SiO2	30	SiO2	1000
SiO2	30	TiO2	70	SiO2	20	TiO2	20	SiO2	20	TiO2	20		
TiO2	80	SiO2	30	TiO2	30	SiO2	20	TiO2	20	SiO2	40		
SiO2	30	TiO2	40	SiO2	20	TiO2	40	SiO2	20	TiO2	30		
TiO2	80	SiO2	20	TiO2	40	SiO2	30	TiO2	20	SiO2	50		
SiO2	30	TiO2	70	SiO2	20	TiO2	20	SiO2	40	TiO2	20		
TiO2	80	SiO2	30	TiO2	40	SiO2	20	TiO2	30	SiO2	40		
SiO2	30	TiO2	40	SiO2	30	TiO2	40	SiO2	20	TiO2	30		
TiO2	50	SiO2	20	TiO2	40	SiO2	30	TiO2	20	SiO2	50		
SiO2	20	TiO2	70	SiO2	20	TiO2	20	SiO2	20	TiO2	20		
TiO2	80	SiO2	30	TiO2	40	SiO2	20	TiO2	20	SiO2	40		
SiO2	30	TiO2	40	SiO2	30	TiO2	40	SiO2	40	TiO2	20		
TiO2	50	SiO2	20	TiO2	40	SiO2	30	TiO2	30	SiO2	40		
SiO2	20	TiO2	40	SiO2	20	TiO2	20	SiO2	20	TiO2	20		
TiO2	50	SiO2	20	TiO2	40	SiO2	20	TiO2	20	SiO2	40		
SiO2	20	TiO2	40	SiO2	30	TiO2	20	SiO2	20	TiO2	20		
TiO2	50	SiO2	20	TiO2	30	SiO2	30	TiO2	30	SiO2	40		
SiO2	20	TiO2	40	SiO2	20	TiO2	20	SiO2	20	TiO2	20		
TiO2	50	SiO2	20	TiO2	30	SiO2	20	SiO2	30	SiO2	50		
SiO2	20	TiO2	40	SiO2	30	SiO2	20	SiO2	40	TiO2	20		

[0047] In an alternative embodiment, multiple thin layers may be deposited on a non planar substrate surface. There are various ways to reshape a flat substrate surface into other kinds of surface profiles. For example, known micro machining techniques can be used to create a curved surface. Gray scale masks can also be

used to create a surface relief pattern on a photoresist film, and such a pattern can be transferred downward to another material below the photoresist film. As is illustrated in Fig. 8, a U-shaped groove 801 can be created in a substrate 802, and a multilayer film 804 made of alternating layers of two materials can be deposited in the U groove (Fig. 8A). A planarization processing step can be used to create the bottom half 805 of a two-dimensional GRIN lens (Fig. 8B). A gray scale mask can be used to make a convex surface profile 806 on the existing half-GRIN structure 805 (Fig. 8C), and more layers 807 can be deposited on top of the convex surface to make a two-dimensional GRIN lens 808 (Fig. 8D) for light focusing applications in which focusing light in both the horizontal and vertical directions is desired. Gray scale mask techniques are used in microlens fabrication and are described in the above referenced co-pending U.S. Patent Application Serial No. 10/083,674.

[0048] It should be noted that structures other than alternating layers of two materials could be used. For instance, a third material (or more) could be added in some alternative embodiments. In another alternative embodiment, small size grains or dots of one material are embedded in another material with the grains or dots having different density and/or grain size distributions in different parts of the material. Also, wires of one material can be embedded into another material, with the wires having a desired distribution of density or size. In addition, a combination of embedded grains and wires could be used, and this could be further combined with thin layers. Thus, any mixture of small size structures may be used to create graded refractive index devices suitable for various applications.

[0049] A variety of materials can also be used, including amorphous and polycrystalline materials. For example, silica (SiO_2 $n=1.45$) and titania (TiO_2 , $n=2.35$) are in common use for making thin film filters for optical fiber communication applications. Due to their relatively large refractive index difference (about 0.9), they can be used to create effective graded refractive index devices for many light focusing applications. A number of other materials may also be used, such as tantalum pentoxide (Ta_2O_5), zirconium oxide (ZrO_2), niobium pentoxide (Nb_2O_5), hafnium oxide (HfO_2), zinc oxide (ZnO), germanium

oxide (GeO_2), lead oxide (PbO), yttrium oxide (Y_2O_3), aluminum oxide (Al_2O_3), silicon carbide (SiC), titanium carbide (TiC), titanium nitride (TiN), chromium nitride (CrN), carbon nitride (CN), carbon boride (CB), aluminum nitride (AlN), zinc selenide (ZnSe), barium fluoride (BaF_2), magnesium fluoride (MgF_2), diamond like carbon (DLC), silicon (Si), germanium (Ge), polyimide, bisbenzocyclobutene (BCB) and cyclized transparent optical polymer (CYTOP). It should be noted that the refractive index of some of these materials is quite large (e.g., for silicon, $n=3.4$). The choice of materials can be varied, depending on the particular application.

[0050] One advantageous choice of materials is silicon (Si) and silica (SiO_2). When Si is combined with SiO_2 , the effective refractive index of the resulting medium can vary by as much as about 1.9. This large variation, combined with the high refractive index of silicon, may be useful in some applications because of the short focal length and small spot size ($0.4\ \mu\text{m}$ in one simulation) that can be achieved.

[0051] GRIN devices according to embodiments of the present invention may be used in any application where there is a need to focus a light beam into a small spot size. For example, such couplers can be used to focus light from a single mode optical fiber into a III-V semiconductor waveguide, in place of objective lenses or lens tipped fibers. Through proper selection of the refractive index distribution, mode matching to the fiber and the semiconductor waveguide can be achieved. Such devices can be fabricated on a substrate as part of an integrated coupler structure that includes a U-groove or V-groove for holding an optical fiber and a photonic chip mounting recess for holding the semiconductor waveguide. Some examples of such optical coupling systems are described in detail in the above referenced co pending U.S. Patent Application Serial No. ____/____ (Attorney Docket No. 10095/19). Still further examples are described in detail in the above referenced co pending U.S. Patent Application Serial No. 10/083,674.

[0052] In addition to light beam focusing, GRIN devices according to embodiments of the present invention can also be used in other applications. For instance, in many near field optics applications, transformation of a light beam

from a mode profile corresponding to a standard single mode optical fiber to a smaller mode size is generally achieved by tapering the fiber to a small tip (e.g., tens of nanometers) at one end and coating the outside of the tapered region with a metal film to prevent light from escaping. In general, most of the light (as much as 99.99%) is lost during this beam size transformation process. Replacing such tapered fibers with GRIN devices according to embodiments of the present invention can improve the transmission efficiency substantially.

[0053] Another application relates to optical data storage, where the storage density can be limited by the spot size of light beams used to record and/or read the data. In existing optical storage devices, discrete optical elements (prisms, lenses, wave plates, etc.) are used to make the optical head and to focus a light beam from a semiconductor laser to a spot size of a few microns. Using a GRIN device according to an embodiment of the present invention, the focused spot size can be made much smaller, and the storage density can be substantially increased. In addition, discrete optical elements can also be replaced with planar light wavecircuit based integrated optics.

[0054] It will also be appreciated that GRIN devices according to embodiments of the present invention allow for fine control and tuning of the refractive index and refractive index distribution to achieve a precise, arbitrary refractive index profile, thereby allowing precise shaping of the optical spot size and mode (wavefront) profile of transmitted light. Thus, such multilayer devices are also suitable for use in a variety of optical applications, including applications where the difference in refractive index is small (e.g., less than 0.2).

[0055] The physical size of the GRIN device can also be varied. For example, a two material device could be constructed for coupling light between a semiconductor laser or detector and a standard multimode fiber, which typically has a mode size of about 50 to 65 microns. It can also be used to couple light from a one dimensional or two dimensional semiconductor laser array or laser bar into a single mode fiber, e.g., for optically pumping an erbium doped fiber amplifier.

[0056] It should be understood that various alternatives to the embodiments of the invention described herein may be employed in practicing the invention. It is

intended that the following claims define the scope of the invention and that methods and structures within the scope of these claims and their equivalents be covered thereby.